SURFACE WATER AND DEPTH PROFILE SPATIAL PATTERNS OF HYPOXIA DEVELOPMENT ALONG THE GRAND STRAND, SOUTH CAROLINA

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REFERENCE: *Proceedings of the 2010 South Carolina Water Resources Conference*, held October 13-14, 2010, at the Columbia Metropolitan Convention Center.

Abstract: Results of intense field sampling for water quality assessment of hypoxia in Long Bay, South Carolina in 2006 (moderate hypoxia), are compared to strategic sampling from 2007 (weak hypoxia) and 2009 (severe hypoxia & anoxia). Results from sampling in 2006 indicated some trends that were persistent in other years including; high chlorophyll (CH) concentrations and lower dissolved oxygen (DO) in bottom waters, constraint of the most compromised water quality to the shallow inner shelf from 0.3–1.0 km offshore, and the centralization of impact in the northern Grand Strand versus shoreline regions in southern Horry county. Analysis of 2006 surface water characteristics from putative terrestrial discharge sites versus control regions did not indicate distinct spatial variability of these regions, but did show clear temporal, and nearshore versus offshore separation. Correlation analysis of the 2006 data revealed that during wet periods salinity was positively related to DO, while in dryer periods it was negatively correlated, suggesting that significant fresh water inputs result in increased heterotrophy and diminished DO in the nearshore. Temporal variability in the extent and magnitude of summertime DO declines in these impacted waters were likely related to spring/summer weather history including temperature and precipitation. Inverse relationships between CH and DO which were found in 11 of 13 category comparisons from 2006 – 2009 suggest that heterotrophic DO consumption overwhelms the capacity for DO production from phytoplankton communities in the shallow inner shelf of Long Bay, South Carolina.

Introduction: Hypoxia conditions (Dissolved oxygen (DO) concentrations $\leq 2.0 > 0.0$ mg/l) in marine and estuarine settings have become more severe increasing in; frequency, duration, and extent worldwide over the last 3 decades (Diaz and Rossenberg, 1995; Wu, 2002; Diaz and Rossenberg, 2008; Conley et al., 2009). Hypoxia can significantly impact biological communities in the coastal ocean with few aquatic species or shallow ecosystems adapted to such low oxygen levels (Boesch and Rabalais, 1991; Baird et al., 2004; Grantham et al., 2004). Considerable evidence suggests that impacts may occur above the hypoxia threshold at concentrations closer to 3 mg/L (Howell and Simpson, 1994; Ritter and Montagna, 1999; Gray et al., 2002). The spatial extent of hypoxia and the more severe anoxia conditions within estuarine and coastal marine environments vary widely, ranging from localized (Chesapeake Bay, Hagy et al., 2004; Kemp et al., 2005) to very expansive (Gulf of Mexico, Turner et al., 2005; Rabalais et al., 2009; Baltic Sea, Conely et al., 2002; Conely et al., 2009b). The spatial characteristics of this phenomenon in terms of influenced area or volume, geographic placement, and by depth - offer some clues as to the mechanisms which act to cause compromised water quality.

The areal extent and volume of hypoxic water within a particular hypoxic zone has been shown to be controlled, in part by nutrient supply. The supply may come from the terrestrial direction in the form of freshwater inputs (Rabalais and Turner, 2001; Kemp et al., 2009; Conley et al., 2009), or from oceanic advection associated with upwelling (Glenn et al., 1996; Glenn et al., 2004). Oxygen concentrations are also modified by water column physical conditions with strong pycnoclines decreasing bottom water DO, by reducing water column mixing and reoxygenation. However microbial DO demand, stimulated by anthropogenic loading of organic and inorganic nutrients, has the capacity to overwhelm even strong columnar mixing to gradually promote hypoxia (Verity et al., 2006).

General circulation models predict that climate change alone will deplete oceanic oxygen by increasing thermal stratification. Globally enhanced discharge of fresh-water and agricultural nutrients are also predicted, which will acerbate hypoxia development (Diaz and Rosenberg, 2009). Climate change induced shifts in wind patterns may also change the spatial patterns of hypoxia, with some coasts experiencing more frequent upwelling conditions which can affect both thermal stratification and nutrient transport (Rabalais et al., 2009b). Added to these eventualities, continued coastal development will provide additional mechanisms to increase nutrient loading and alter coastal water hydrology in manners that will also enhance hypoxia development (Kleppel et al., 2006).

Methodology: High spatial resolution maps of surface water temperature, salinity, pH, dissolved oxygen (DO), colored dissolved organic matter (CDOM), chlorophyll *a* (CHL), were obtained with flow-through Dataflow^{TM} instrumentation. The results from the chlorophyll sensor were intercalibrated with measurements via acetone extraction (EPA 445.0). All other probes were calibrated pre and post sample collection following manufacturer guidelines. Contour maps were generated according to Boynton and Rohland (2001) using the ESRI ArcGIS 8.1.2 software suite to assist in the interpretation of spatial patterns of different water quality parameters. Interpolation was accomplished using Kriging routines in the Geostatistical Analyst extension within the ArcGIS software.

Results and Discussion: Weather conditions in 2006 (Table 1) indicated that precipitation displayed greater than a 2 order of magnitude range across sampling dates. Wind direction displayed a relatively narrow range of directions from 152 – 228 compass bearing, with the exception of 7/10/06 in which wind was oriented from 96 degrees. Wind speed showed less variability (<2x range). Notably the last 6 dates provide a fortunate coincidence of 3 pairs of contrasting wet and dry dates separated by approximately the same time interval. Winds were generally from the southeast which under prolonged periods would promote Ekman transport offshore and upwelling along the coast. Wind speed and direction of 7/10/06 represented calmest conditions and minimum potential for shore perpendicular water transport.

Table 1. Mean weather conditions based upon a 5 day interval prior to cruise date. Weather data is from the National Weather Service records from North Myrtle Beach airport. Variables include; Precipitation (PREC., mm/d), Wind direction (WINDR, ° compass bearing), and Wind speed (WINSP, miles/hr).

Date	*Mean ± SD, PREC.*	*Mean ± SD, WINDR*	*Mean ± SD, WINSP*
4/26/06	0.41 (0.57)	196 (54)	9.84 (1.34)
5/29/06	0.03 (0.05)	162 (99)	9.22 (4.33)
7/10/06	0.07 (0.17)	96 (77)	5.62 (1.82)
7/27/06	0.43 (0.66)	212 (8)	5.74 (1.44)
8/7/06	0.09 (0.19)	152 (76)	6.08 (2.16)
8/24/06	0.70 (1.44)	192 (53)	8.58 (4.89)
9/04/06	1.44 (3.21)	228 (80)	6.56 (3.42)
9/27/06	0.01 (0.01)	170 (87)	7.88 (5.26)

Table 2. Descriptive statistics for surface water *in vivo* fluorescence (CHL, relative fluorescence units) and dissolved oxygen (DO, mg/l) for all observations on each cruise date in 2006. Statistical parameters include range and mean. Dates indicated by yellow shading included depth profile data collections.

Date	*CHL Min - Max*	*CHL Mean*	*DO Min - Max*	*DO Mean*
4/26/06	0.108-0.601	0.252	7.07-12.23	9.46
5/29/06	0.084-0.688	0.147	6.70-8.72	7.02
7/10/06	0.134-1.665	0.347	5.43-6.56	6.22
7/27/06	0.139-0.759	0.249	2.59-7.27	6.11
8/7/06	0.095-0.895	0.230	5.99-13.04	7.79
8/24/06	0.184-1.029	0.353	5.70-7.12	6.72
9/04/06	0.121-0.793	0.289	4.30-6.45	5.59
9/27/06	0.163-0.646	0.322	6.53-7.61	7.24

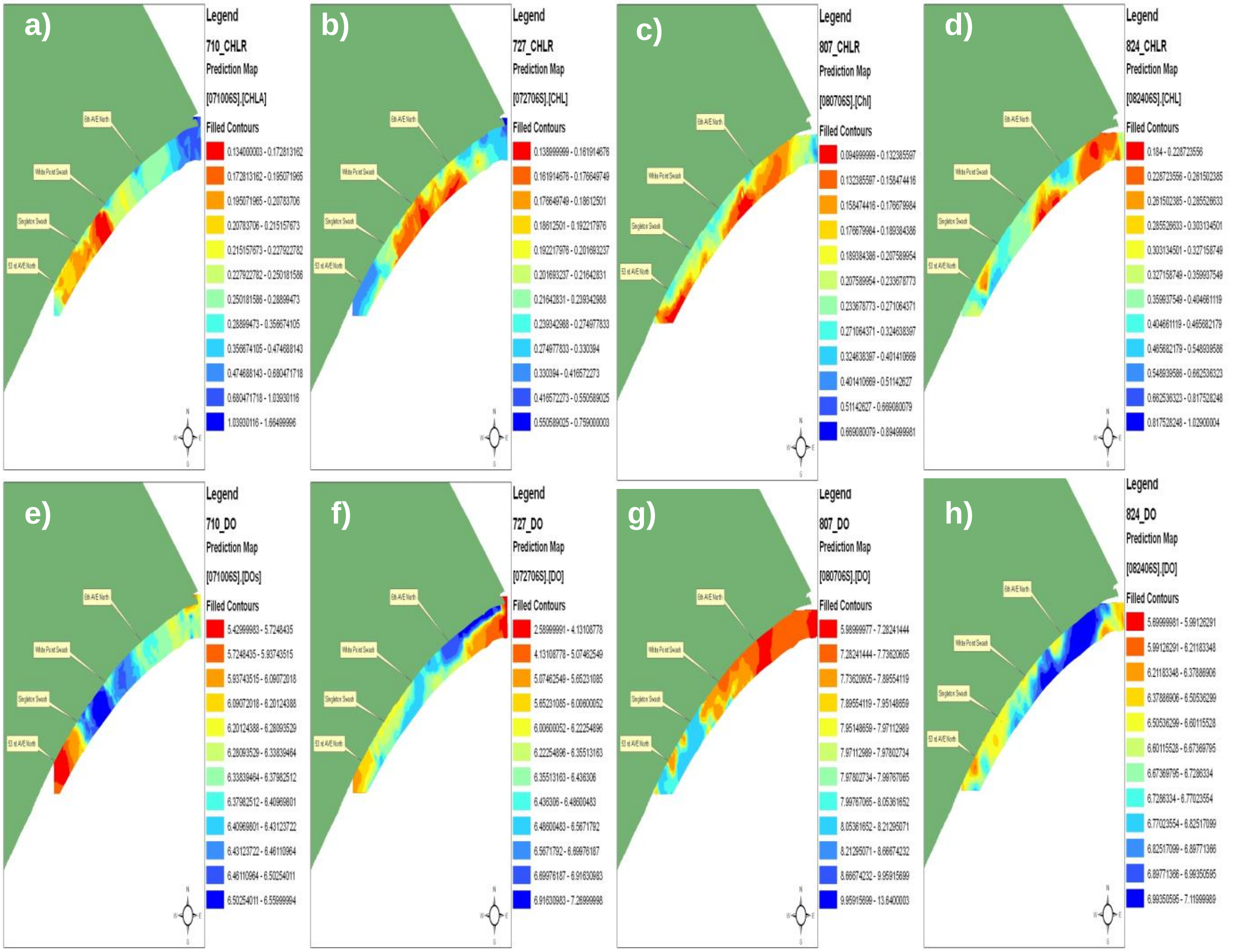

Figure 1. High resolution spatial maps of Chlorophyll *in vivo* fluorescence and Dissolved Oxygen within the northern study region. Chlorophyll values are shown in a-d, while Dissolved Oxygen are shown in e-h. Alphabetical order of each variable represents sequential sampling dates in June and July. Scale bars display low values in red grading to high values in dark blue.

Surface water mapping of CHL and DO (Figure 1) focused on the northern most sites in our survey region because of the continuity of data over all cruises in that region. Results indicate complicated spatial variability which included; dates in which CHL and DO display primarily longshore variability, dates in which the variability was primarily inshore / offshore, and other dates with roughly equal contributions of longshore and offshore components. Spatial patterns of both CHL and DO displayed the most longshore and least offshore variation on 7/10/06 when the wind field was from 90 degrees. Regarding CHL the two wettest dates 8/24/06 and 9/04/06 (not shown) both displayed mostly longshore variability, while for DO these dates had more equal variability components. The gradient of longshore variability was often not precisely shore parallel but often manifested along a north / south axis.

Depth profile data was obtained from the 4 cruises which were conducted in July and August of 2006. Data from the northern four sampling sites including; 6th Ave N. (North Myrtle Beach), White Point swash, Singleton swash, and 53rd Ave. (Myrtle Beach) are shown below for the date of 7/10/06. This date resulted in the most extreme suboxic conditions (<4 and >2 mg/l of O2) in bottom waters. Figure 2 indicates that the sites had very strong differences in inshore versus offshore depth profiles of chlorophyll, with inshore sites higher in chlorophyll at all depths but especially in the bottom waters. Bottom waters at all 16 sites surveyed on this date displayed higher chlorophyll concentrations versus that observed in the surface waters.

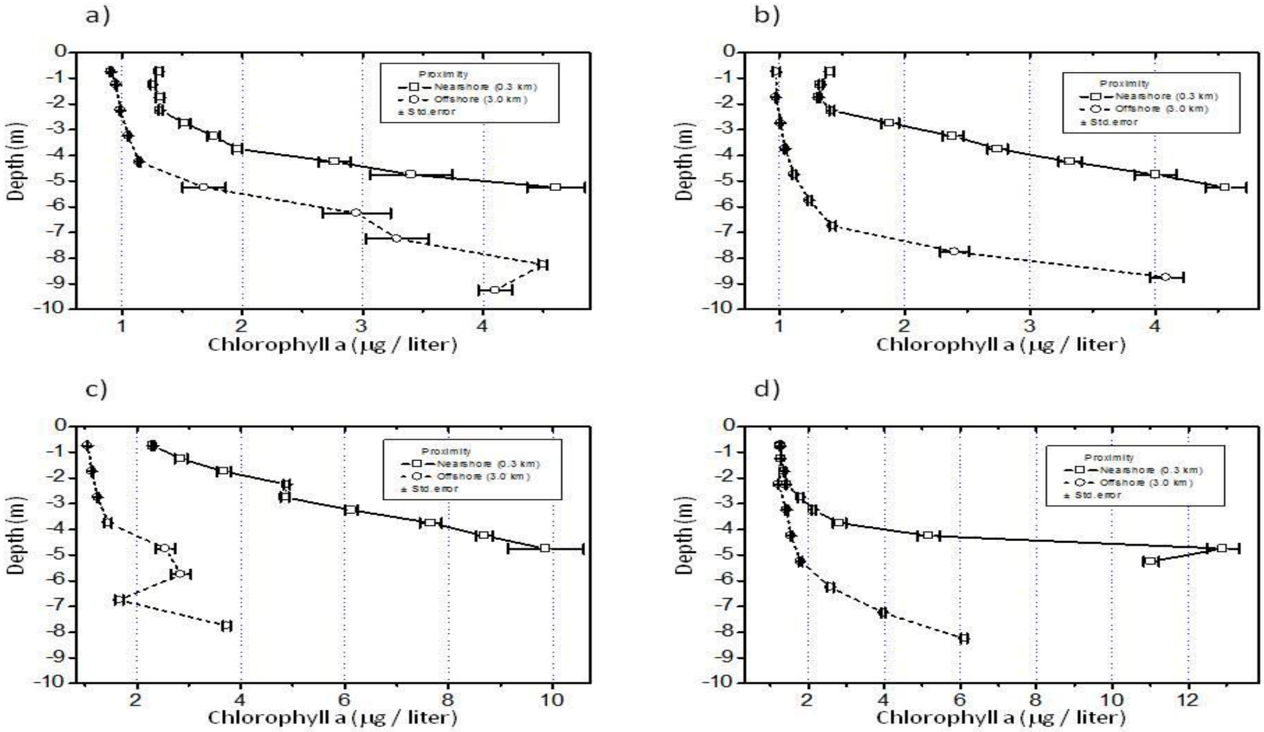

Figure 2. Depth profiles from 7/10/06 of estimated chlorophyll concentration (based on *in vivo* fluorometer vs extracted CH regression) at the northern four study sites including; 6th Ave N. (North Myrtle Beach), White Point swash, Singleton swash, and 53rd Ave. (Myrtle Beach). Solid lines indicate inshore profiles while dashed lines indicate offshore profiles.

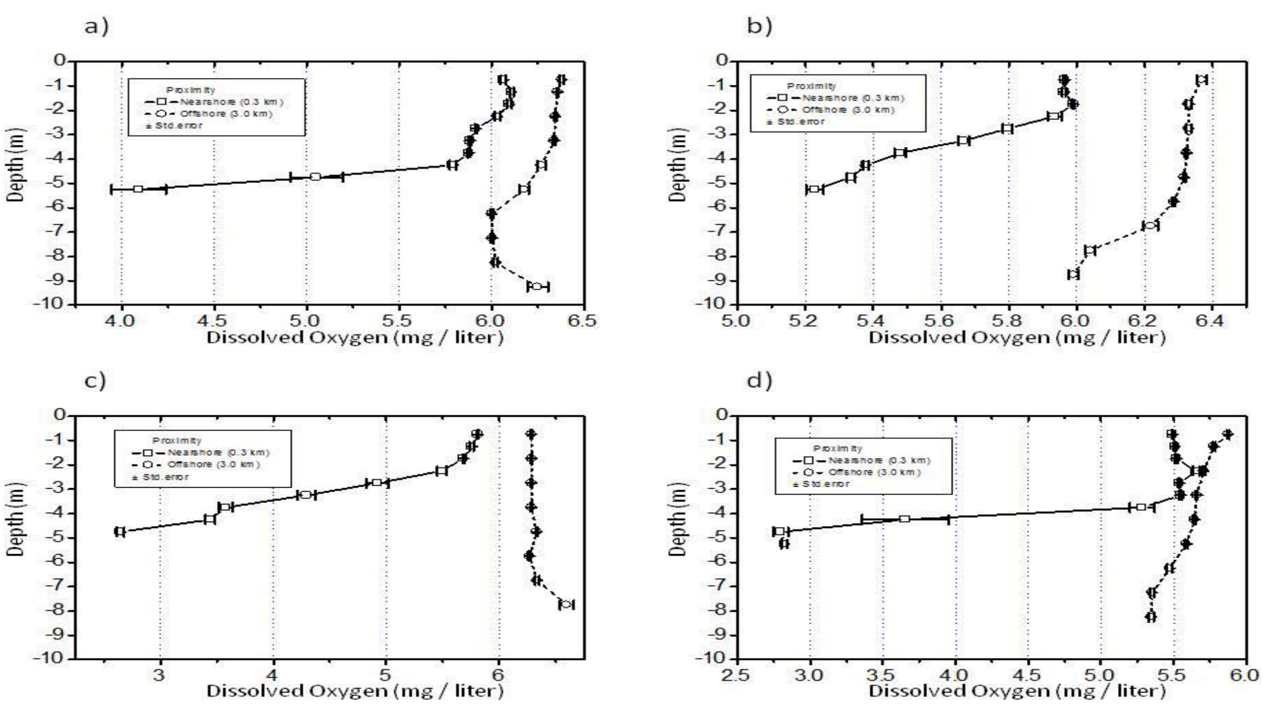

Figure 3. Depth profiles from 7/10/06 of dissolved oxygen readings at the northern four study sites including; 6th Ave N. (North Myrtle Beach), White Point swash, Singleton swash, and 53rd Ave. (Myrtle Beach). Solid lines indicate inshore profiles while dashed lines indicate offshore profiles.

Concentrations of dissolved oxygen (Figure 3) also displayed very significant differences between inshore and offshore locations. In figure 3, depth profiles of DO revealed a strong inverse relation to chlorophyll concentration with inshore sites having lower DO at all depths and strong oxyclines compared with offshore sites. These trends suggest that in this case the mechanism responsible in generating the low DO was not associated with advection of high chlorophyll and low DO water masses from offshore.

Additional analysis of the surface data utilized selection of 1.1 km2 regions of interest (ROI) about putative stormwater discharge sites (d) and control regions (c) between these sites. This selection was performed in both the inshore (in, 0.3 km from coast), and offshore (off, 3.0 km from coast) locations. We then determined the mean value of attributes for water temperature, salinity, pH, dissolved oxygen, colored dissolved organic matter (CDOM), and chlorophyll *a*. ROI selections and means were determined for the last 4 survey dates and analyzed by numerical clustering (Figure 4) and correlation (Table 3).

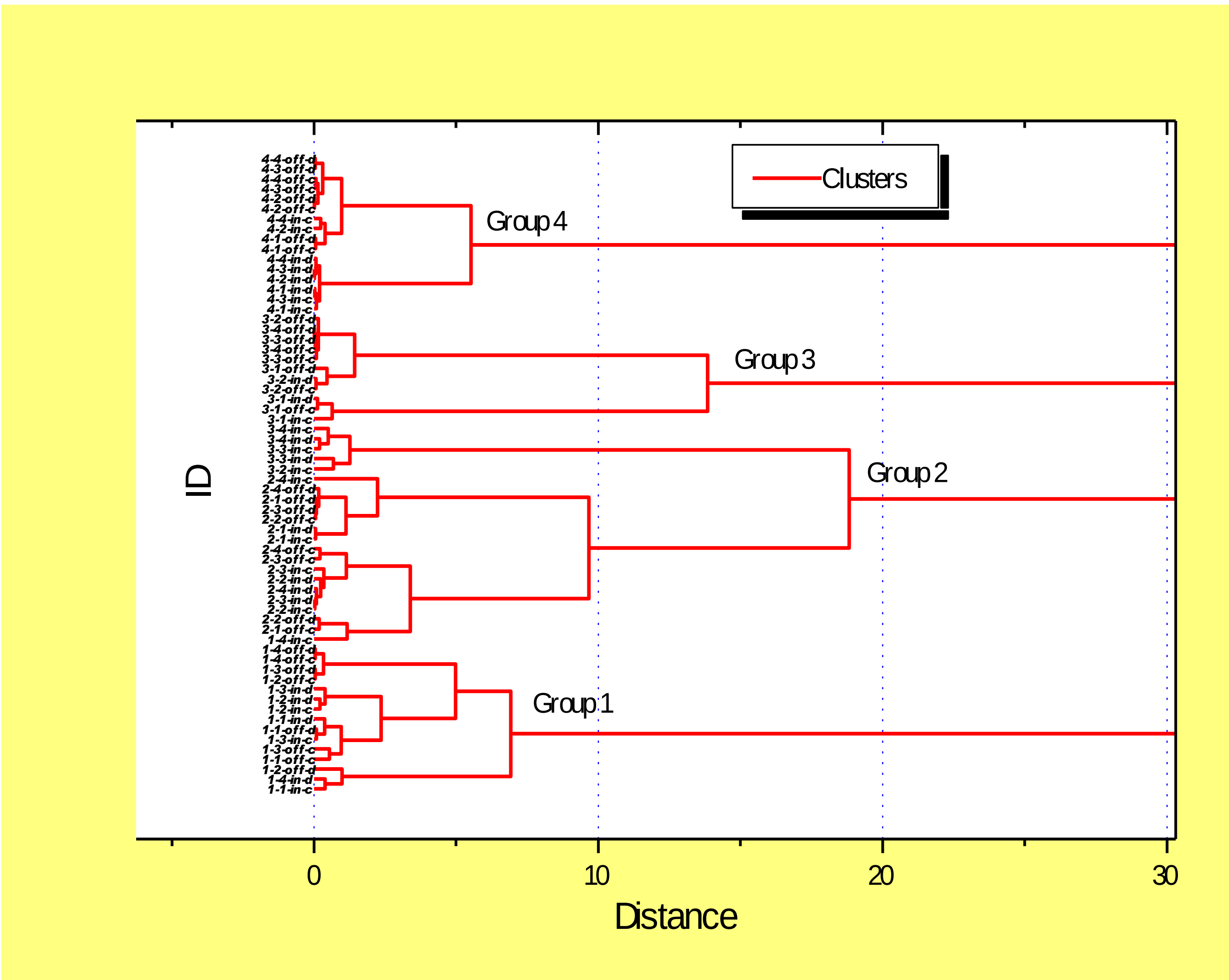

Figure 4. Numerical clustering using Ward's method of region of interest observations of Dataflow parameters. ID designations are based upon; date (1=8/07, 2=8/24, 3=9/04, and 4=9/27), followed by station (1=6th ave. North Myrtle Beach, 2=White point swash, 3= Singleton swash, and 4= 53rd ave. Myrtle Beach), followed by proximity (in=inshore, off=offshore), and discharge characteristics (d=discharge site, c=control site).

Numerical clustering by Wards method (Figure 4) revealed 4 large cluster groups which were highly date specific. The smaller cluster structure within each date cluster appeared to be associated with proximity to the coast. Clustering analysis was unable to detect significant differentiation of discharge versus control sites for these wet versus dry dates, but did overlap regarding dates with inshore sites during date 3 mixing with all of date 2 in cluster group 2. The lack of discharge site separation versus control regions may be due to rapid shore parallel mixing.

Correlation analysis of the ROI data from above, combined discharge and control sites (which had undetectable separate structures in clustering) to better examine date and proximity effects upon variable inter-relationships. The frequency of correlations differed by date with 9/04/06 displaying 15 of 20 possible significant correlations, while other dates were roughly 10 of 20. Similar to the clustering analysis results, there were little similarities between correlation patterns by date.

One robust relationship that was found over all dates was that between pH and DO. Each inshore comparison showed a highly significant positive relationship between these variables, and similar relationships were also observed on 3 of 4 dates for offshore comparisons. This strong relationship suggests that DO is governed by the balance between autotrophic and heterotrophic production processes, which also markedly influence water pH. Another important relationship that was dynamic was the correlation of DO to salinity. Note the negative correlations to inshore salinity on the first and 3rd dates, while on the second date the relationship was highly positive. Combined with the precipitation records for these dates, these results suggest that significant precipitation events and freshwater inputs into the inshore sites lead to a decreased DO (heterotrophic response), while under low freshwater input conditions lower salinity conditions are associated with higher DO (more autotrophic conditions). This fluctuating relationship to salinity may be reflective of time course changes in the heterotrophic response to inputs from natural and anthropogenic discharges.

Table 3. Correlation analysis of all ROI data by date and proximity. Dates (upper left number values) are as in Figure 2. Within each cell upper value is correlation coefficient (r), middle value is observation number (n), and lower value is the significance value (p) of the correlation. Only correlations with significance values of <0.0001 are shown.

1)	Inner CHL	Inner DO	Outer CHL	Outer DO
DO	-0.62564 167 7.88E-20		-0.02359 260 0.35248	
pH		0.53485 167 4.83E-14	-0.3089 260 1.87E-07	
TEMP	-0.41017 167 1.85E-08		0.23664 260 5.85E-05	
SAL		-0.32712 167 7.98E-06		-0.42159 260 6.29E-13
CDOM		-0.39789 167 5.05E-08		

2)	Inner CHL	Inner DO	Outer CHL	Outer DO
DO			-0.43669 141 3.09E-08	
pH		0.83227 216 0	-0.55415 141 5.07E-13	0.90555 141 0
TEMP	0.33552 216 2.21E-07		-0.32515 141 4.18E-05	0.64553 141 2.77E-18
SAL		0.61505 216 3.61E-24		0.6988 141 2.86E-22
CDOM		-0.65642 216 2.64E-28		

3)	Inner CHL	Inner DO	Outer CHL	Outer DO
DO	-0.67334 318 1.19E-43		0.36338 119 2.43E-05	
pH	-0.84612 318 0	0.80525 318 0	-0.32853 119 1.32E-04	
TEMP	-0.43879 318 1.07E-16	0.70891 318 0	0.29342 119 6.00E-04	0.4637 119 5.45E-08
SAL	0.23366 318 1.28E-05	-0.50289 318 4.36E-22		-0.56136 119 1.56E-11
CDOM		0.20806 318 9.32E-05	0.3074 119 3.36E-04	0.52725 119 3.63E-10

4)	Inner CHL	Inner DO	Outer CHL	Outer DO
DO			-0.41929 118 1.15E-06	
pH	-0.43439 382 2.59E-19	0.67751 382 0	-0.77243 118 6.40E-25	0.5273 118 4.27E-10
TEMP		0.88744 382 0	-0.68545 118 5.53E-18	0.68349 118 7.43E-18
SAL	-0.22677 382 3.80E-06		-0.29112 118 6.91E-04	
CDOM		-0.46928 382 1.29E-22		

Table 4. Linear regression statistics of chlorophyll *a* (CH) versus dissolved oxygen (DO) based upon depth related sampling over selected cruise dates in 2006, 2007, and 2009. Locations in 2006 and 2007 are from the northern region of survey areas and include; 1) 6th Ave. S. North Myrtle Beach, 2) White Point Swash, 3) Apache Pier, and 4) 53rd Ave Myrtle Beach. Mean bottom depths for nearshore and offshore samplings in 2006 and 2007 were 5.36, 8.75, 3.0, and 6.5m respectively.

Date	*Locations*	*Depth / Proximity*	*Formula*	*n*	R^2	*p value*
7/10/2006	1-4	All	DO = -0.31(CH) + 6.51	644	0.72	<0.0001
7/10/2006	1-4	Surface	DO = -0.41(CH) + 6.61	82	0.41	<0.0001
7/10/2006	1-4	Bottom	DO = -0.45(CH) + 7.64	62	0.68	<0.0001
7/10/2006	1-4	Nearshore	DO = -0.32(CH) + 6.34	333	0.82	<0.0001
7/10/2006	1-4	Offshore	DO = -0.11(CH) + 6.32	311	0.19	<0.0001
7/24/2007	1-4	All	DO = -0.09(CH) + 7.01	211	0.54	<0.0001
7/24/2007	1-4	Surface	DO = -0.17(CH) + 7.27	24	0.25	0.010
7/24/2007	1-4	Bottom	DO = -0.08(CH) + 6.84	23	0.53	<0.0001
7/24/2007	1-4	Nearshore	DO = -0.03(CH) + 6.88	97	0.22	<0.0001
7/24/2007	1-4	Offshore	DO = -0.10(CH) + 6.90	114	0.68	<0.0001
8/20 & 8/27/2009	14 stations*	All	DO = -0.07(CH) + 4.08	38	0.20	0.002
8/20 & 8/27/2009	14 stations*	Surface	DO = -0.10(CH) + 4.58	19	0.05	ns
8/20 & 8/27/2009	14 stations*	Bottom	DO = -0.03(CH) + 2.98	19	0.04	ns

The inverse correlative relationship between CH and DO, which was very found in 11 of 13 category comparisons from 2006 – 2009 (Table 4), indicates that heterotrophic DO consumption typically overwhelms the capacity for DO production from phytoplankton communities in the shallow inner shelf of Long Bay, South Carolina. Further, locations with water depths of ca. 5-7 m, and the bottom water samples from those sites show the best R^2 value regarding the regression relationship. The restricted nearshore and bottom water area where CH was high (Figure 2) and DO markedly low (Figure 3) suggests a hypoxia production mechanism where both autotrophic and heterotrophic populations are enhanced within a very narrow nearshore width. Such a spatial pattern of hypoxia in coastal waters, has not been previously reported in the literature (Kemp et al., 2009; Rabalais et al., 2009), and may emanate from a yet unidentified mechanism. Inter-annual variation in hypoxia was obvious over the course of the study. Comparisons between 2006 (a moderate hypoxia year) & 2007 (a weak hypoxia year) as outlined in table 4 indicated generally weaker correlation statistics for 2007. Weather comparisons between 2006 and 2007 (NOAA-NCDC, data not shown) indicated greater precipitation in 2006 preceding the summer hypoxia trending months (July / August). The most compromised water quality, was unfortunately not well sampled (statistically weak) and occurred in 2009 where true anoxia was recorded for several short periods.

Conclusions and Relevance: This several year field study has documented a spatial pattern of hypoxia in shallow South Carolina coastal waters that has not been described in previous scientific literature. The hypoxia which occurs here has an extremely limited distribution offshore, but has been found to occur over 10s of kilometers of the coastline. The most impaired conditions occur from 0.3 – 1.0 km offshore in the North Myrtle beach area of the Grand Strand, and appear to require upwelling favorable winds and recent terrestrial runoff for maximum development. Hypoxia tends to occur in summer and early fall, but shows significant inter-annual variability. The nearshore location of this hypoxia, place it squarely in the central tourism attraction of the state. The number of recreational / commercial resources threatened by hypoxia are numerous and include among others; beach goers, pier fishers, shallow charter fishers, ocean pleasure craft operators, shallow water demersal fish (i.e. Flounder), shallow water pelagic fish (i.e. Kingfish), baitfish, shrimp, and a host of other food web members. A recent collaborative study between S.C. DNR and CCU (Johnson et al., 2007) has documented strong changes in the community structure of recreational fish landings from our local piers. Amongst these changes Kingfish have decreased dramatically. The study also found that the annual shallow charter fishing landings as recorded by the National Marine Fisheries Service seem to be highly influenced by spring-summer winds and river discharge – the same meteorologic factors that appear to influence shallow water hypoxia. Although scientifically we cannot definitively indentify the reason behind these changes, one plausible mechanism is fish avoidance of impaired waters. Coastal managers need to be aware of this issue and to affect whatever mitigating measures (i.e. high nutrient runoff) under human control in order to protect our most valuable coastal resources.

Acknowledgements: This study was funded through grants from S.C. Sea Grant Consortium and S.C. Department of Health and Environmental Control. Greatly appreciated was the field assistance from Jamie Phillips, Sam Lake, Emma Wear, Ben Burroughs, and Melisa Day. Finally, I am indebted to the research team from the Long Bay Hypoxia Research Group, especially those who are also contributing to these conference proceedings, which include: Susan Libes, George Voulgaris, Erik Smith & Denise Sanger.

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